

LERC IN-HOUSE EXPERIMENTAL RESEARCH

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LeRC In-House Experimental Research

The Lewis Research Center has an ambitious in-house experimental research program to conduct studies, acquire technology, and validate the capabilities and limitations of advanced low NO_x combustor concepts. This program will establish NO_x reduction technologies that will insure no significant ozone depletion in the atmosphere by future high speed civil transports (HSCT). This is critical to establishing the environmental feasibility of an HSCT. This work supports the efforts of industry and universities to determine the criteria for the HSCT combustor concept selection in 1992. The work at Lewis focuses on several flame tube combustor rigs: the Lean Premixed Prevaporized (LPP); the Rich Burn/Quick Quench/Lean Burn (RQL); the Catalytic Oxidation Rig; and the Ceramic Matrix Liner Test Rig. Advanced laser diagnostics will be applied to the flame tube rigs to provide more detailed and non-intrusive measurements of combustion flow parameters.

- **Lean Premixed Prevaporized (LPP)**
- **Rich \ Quick Quench \ Lean (RQL)**
- **Catalytic Oxidation Rig**
- **Ceramic Matrix Liner Rig**
- **Diagnostics**

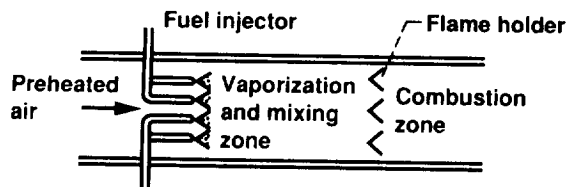
Combustion Concepts

The basic approach to thermal NO_x reduction is to reduce the flame temperature. This can be accomplished by burning lean or rich, avoiding the maximum flame temperature which occurs near the stoichiometric equivalence ratio (E.R.) of 1.0. The three concepts shown on this figure reduce NO_x emissions by burning lean (E.R. of 0.6) for the Lean Premixed Prevaporized (LPP) concept, or by burning rich (E.R. of 1.2-1.8) and then lean (E.R. of 0.6) for the Rich burn/Quick Quench/Lean Burn (RQL) concept, or by burning very rich (E.R. of 3-9) for the Catalytic Oxidation section which could be used as the rich stage for the RQL concept. These concepts are the focus of our LeRC in-house experimental efforts.

Combustion Concepts

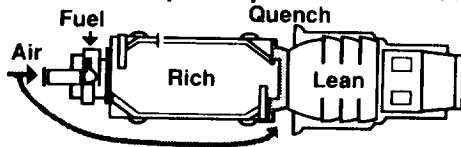
Common approach: Reduce thermal NO_x formation by reducing flame temperatures

Lean premixed/prevaporized



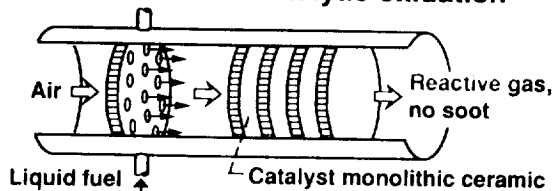
- Burning with excess air in lean zone; equivalence ratio = 0.6

Rich burn/quick quench/lean burn



- Burning with excess fuel; equivalence ratio = 1.2 - 1.8
- Burning with excess air; equivalence ratio = 0.6

Rich zone variant catalytic oxidation

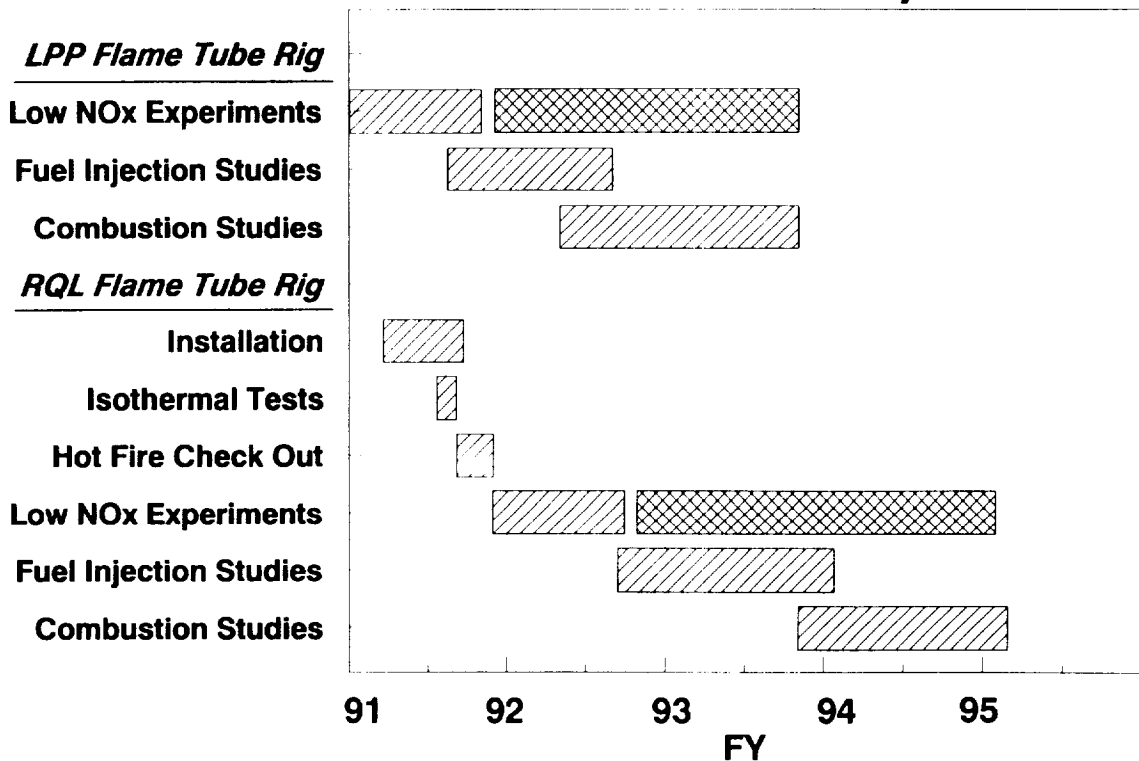


- Catalytic burning highly excess fuel; equivalence ratio = 3.0 - 9.0

Schedule for In-House Experiments

The schedule below shows the general time-frame for the major phases of the experimental work which will be performed in the LPP and RQL flame tube rigs. The term "Low NOx experiments" initially refers to the gas sampling probe measurements of gaseous emissions for various equivalence ratios and inlet pressures and temperatures. This activity is continued into a second phase which includes the use of advanced diagnostic probes through windowed sections in first the fuel/air mixing zones and then in the combustion zones of each of the flame tubes. A little more detail is given for the RQL rig which is currently in its isothermal testing phase. Within the next few weeks, the hot fire check-out will occur and the initial low NOx testing can begin.

Schedule for LPP & RQL Flame Tube Experiments



Lean Premixed Prevaporized Combustion

The objective of this portion of the LeRC in-house research program is to use a flame tube combustor to demonstrate the capability of the Lean Premixed Prevaporized (LPP) concept to reach the HSR goal of a NO_x emission index (grams of NO_x produced per kilogram of fuel burned) of between 3 and 8. Using the flame tube combustor, the effect of fuel/air distribution and degree of vaporization can be studied. Also of great interest are autoignition, flashback, turbulent mixing and lean stability. Information obtained in the flame tube about these parameters will be used to guide the design of an LPP combustor.

The approach is to use an existing NASA-designed square cross-section flame tube combustor to allow combustion testing at the high temperatures and pressures necessary for the HSR Program. This rig was designed in the late 70's to support the emissions reduction program at that time. It has a windowed section to allow laser diagnostics to probe the premixing zone. A windowed section is currently being designed to accommodate laser studies of the combustion zone.

OBJECTIVE:

- ☐ **Demonstrate the Capability of LPP to Reach the HSR Goal of NO_x E.I.'s Between 3 and 8 g/Kg**
- ☐ **Experimentally Study the Effect of Fuel/Air Distribution Degree of Vaporization, and Additives on the Emission of NO_x for Advanced Low NO_x Combustors**
- ☐ **Study Autoignition, Flashback, Turbulent Mixing and Lean Stability.**

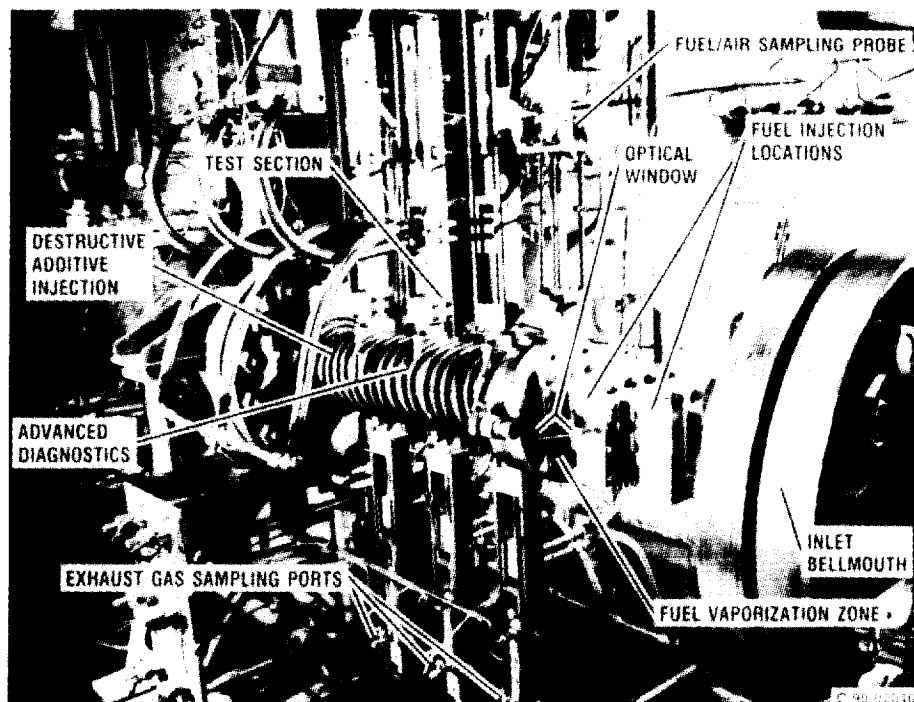
APPROACH:

- ☐ **Use Existing NASA Square Cross-Section Flame Tube Combustor to Reach High Temperatures and Pressures Necessary for HSR Program.**
- ☐ **Use advanced laser diagnostics to obtain measurements and use in code validation.**

Lean Premixed Prevaporized Combustion LeRC Square Flame Tube Rig

The rig is shown schematically in this figure. The airflow, up to 5 lbs./second, 1100 F inlet temperature, 20 atmospheres pressure, passes from a large round-cross-sectional flow straightening plenum into a 3-inch square inlet section which leads to a multiple-conical tube fuel injector (shown later). The fuel injector can be moved by rearranging the configuration of several spool pieces so that fuel vaporization as a function of distance downstream of the fuel injector can be studied. One configuration includes the addition of a windowed section downstream of the fuel injector to allow flow visualization and laser diagnostic measurements of the degree of vaporization and droplet sizes and velocities. Just before the flame holder, a sampling probe allows sampling of the fuel/air mixture. The flameholder is an 80%-blockage, uncooled perforated plate, soon to be replaced with a water-cooled flameholder for more durability. The rig is ignited by a spark igniter, surrounded by a water-cooled jacket. The combustion section is lined with a castable silicon-carbide ceramic, which is poured around a 3-inch square wooden mold to form the test section passage and is externally water-cooled with copper cooling coils. There are 6 gas sampling probes located at 3 axial locations and 2 "radial" locations at each axial station. A windowed section for the combustion zone is planned to be ready early in 1992.

HSR Square Flame Tube Rig Lean Premixed Prevaporized Combustion (LPP)

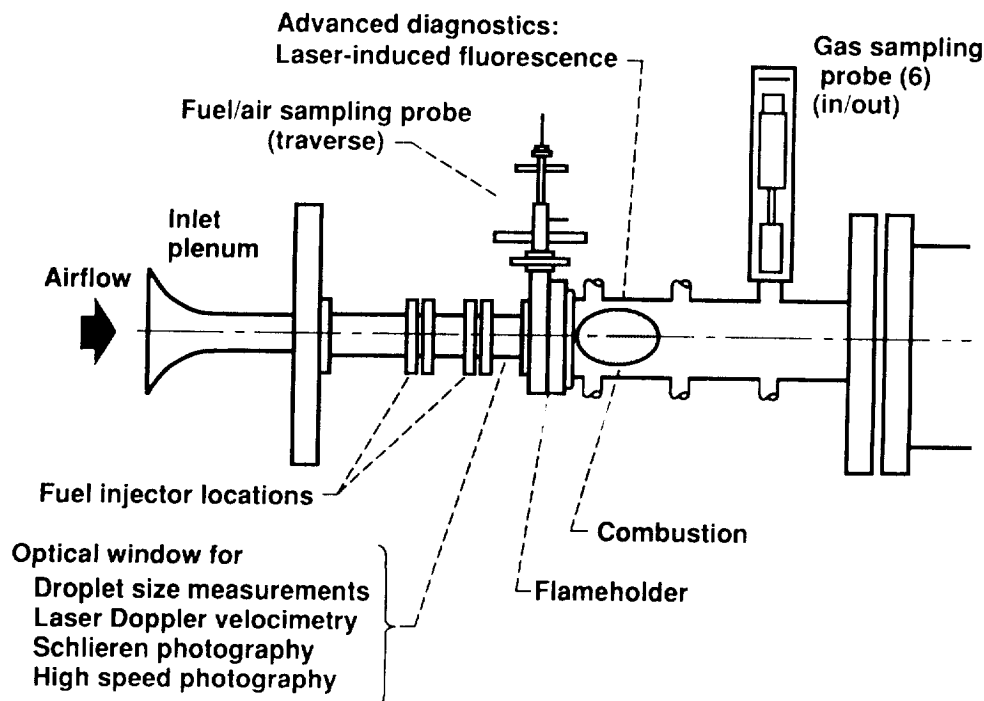


Lean Premixed Prevaporized Combustion

Photograph of LPP Rig

The LPP flame tube rig is shown in the photograph below. The non-vitiated pre-heated air passes into the rig from the right-hand side of the picture through the inlet bellmouth, where the transition from round inlet section to square test section occurs. Two possible fuel injection locations are shown and the location of the optical window section can be seen as part of the fuel vaporization zone. At the end of the fuel vaporization zone is a fuel/air sampling probe. The round flange shows the location of the flame holder, downstream of which is seen the cooling coils surrounding the combustion test section. The six exhaust gas sampling ports can be seen below and above the test section. A future windowed section will be added to allow use of advanced diagnostics in the combustion zone. The destructive additive injection called out in the photograph was an experimental program planned to verify the results of an analytical evaluation of NO_x destructive additives. However, since the analytical results showed no viable NO_x destructive additives for HSR applications, this experimental program is not expected to be carried out.

Lean Premixed/Prevaporized Combustion (LPP) LeRC Square Flame Tube Rig

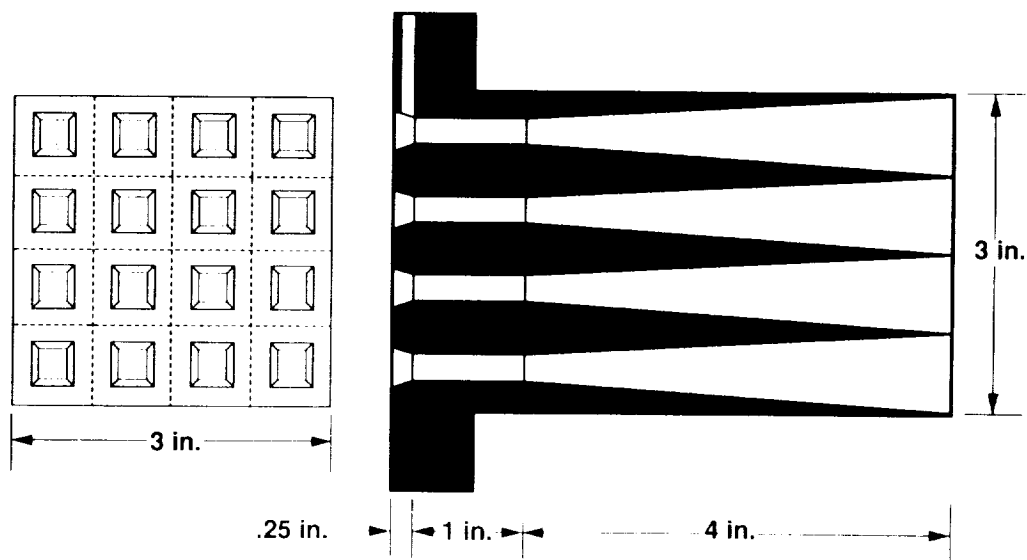


Lean Premixed Prevaporized Combustion LPP Multiple Tube Fuel Injector

A key subcomponent is the fuel injector. A unique multiple tube fuel injector is being used in the square flame tube rig at LeRC. Shown schematically below, there are 16 fuel injection passages which use the Venturi effect to provide high velocity airflow to break up the fuel into fine droplets. Very small fuel tubes enter the Venturi passage and curve around so that the fuel is injected parallel to the airflow. A small amount of air passes over these small tubes to cool them as they make their way through the fuel injector body into the Venturi passage.

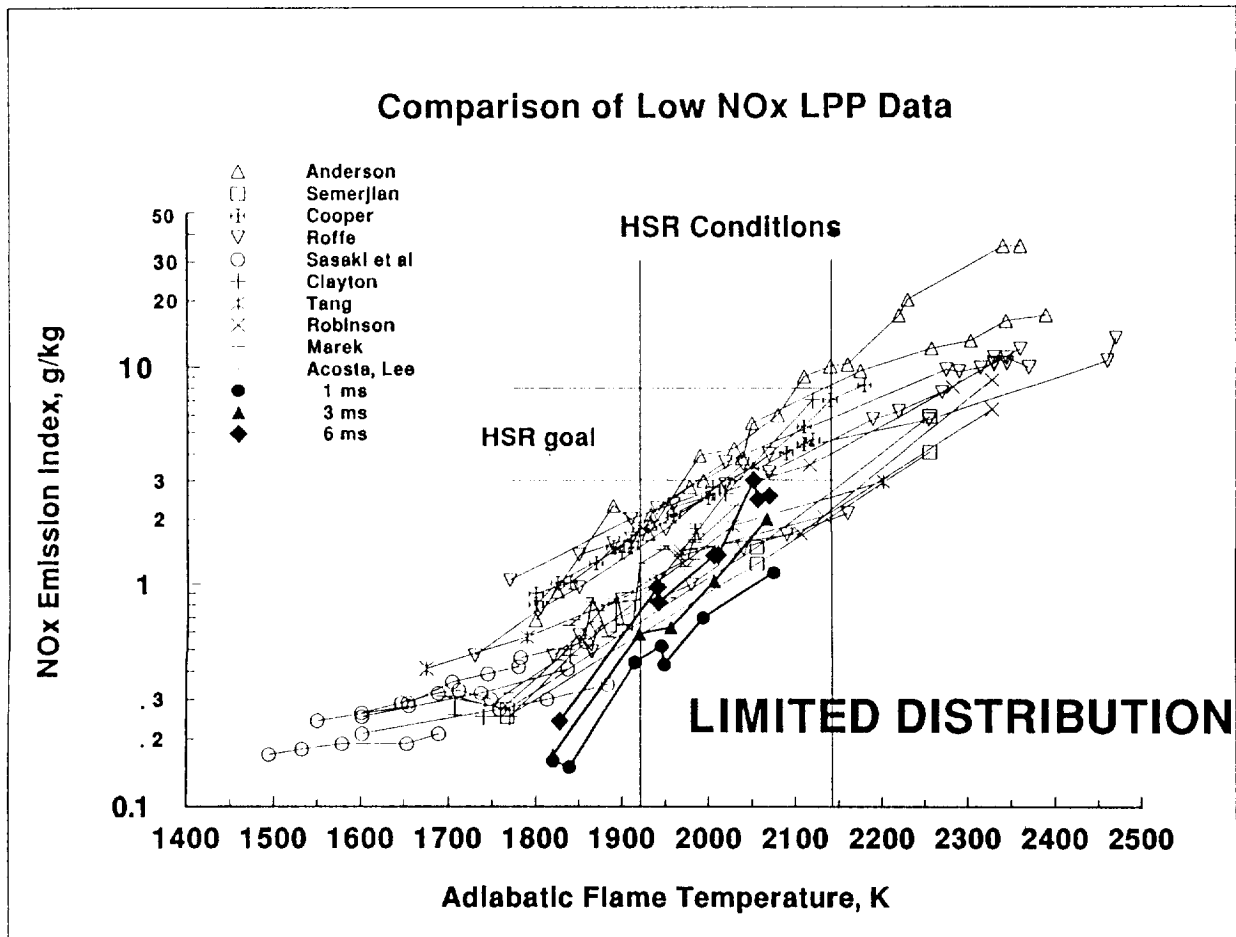
In-house water cold flow studies on one fuel passage of this fuel injector has shown that it is capable of producing extremely small droplets (on the order of 10 microns in diameter). The NO_x data obtained using this multiple tube injector was lower by an order of magnitude compared to some preliminary NO_x data obtained with a crude "spray-bar" fuel injector in the same flame tube rig.

LPP Multiple Tube Fuel Injector



Comparison of Low NO_x LPP Data

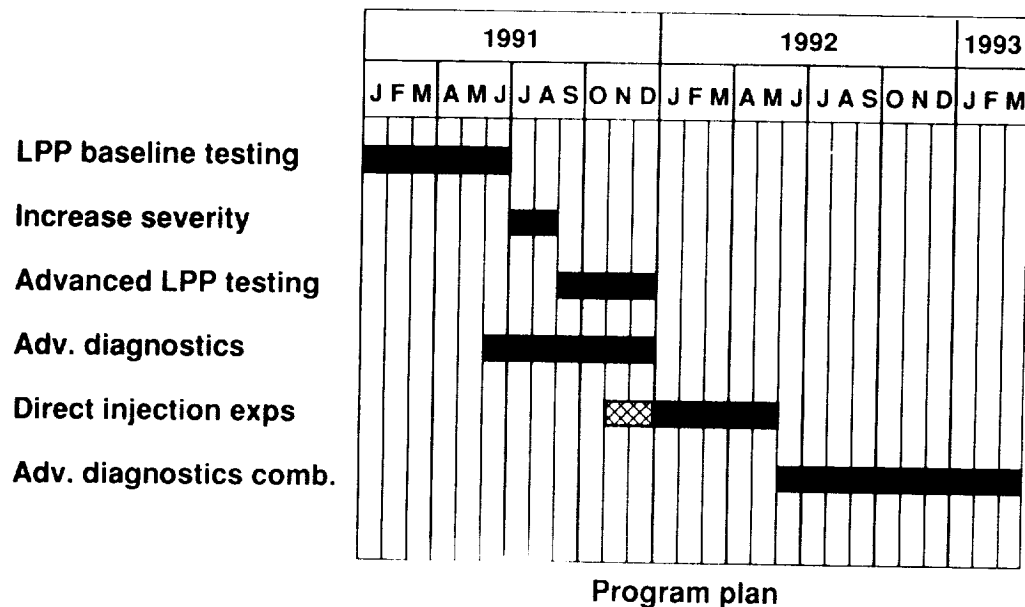
The figure below shows the emission index of NO_x (grams per kilogram fuel burned) as a function of adiabatic flame temperature in the combustion chamber. The figure is a historical representation of NO_x measurements from several research programs which studied lean premixed prevaporized combustion. The most recent results are those obtained from the LPP square flame tube rig at LeRC by Acosta and Lee. This data is shown as filled-in symbols and show encouragingly low NO_x emissions. These NO_x emissions are well within the HSR goal (less than 8 gm. NO_x/kg. fuel) at conditions representative of HSR combustor operating temperatures and pressures shown between the vertical bars.



Lean Combustion Studies Timeline

The program plan for the LeRC in-house testing is shown in the figure below. Currently baseline testing is being performed to define the operating conditions for the LPP flame tube rig. This includes determining the lean stability limits, flashback and autoignition limits and flameholder and liner characteristics and durability. During this period, low NO_x was successfully demonstrated at HSR cruise conditions. In the near future, a new preheater will enable even higher inlet temperatures to allow operation of the rig at increased severity parameters. Installation of the water cooled flameholder will then allow "advanced LPP testing" at the higher temperatures and pressures. Advanced diagnostics will be used to study the fuel vaporization and mixing process downstream of the fuel injector within the next few months. By the middle of 1992, the window section will be installed in the combustion zone and advanced laser diagnostics will be used to study the combustion process itself.

Lean Combustion Studies



Rich Burn/Quick Quench/Lean Burn (RQL)

The objective of this portion of the LeRC in-house research program is to use a flame tube combustor to demonstrate the capability of the Rich Burn/Quick Quench/Lean Burn (RQL) concept to reach the HSR goal of a NO_x emission index (grams of NO_x produced per kilogram of fuel burned) of between 3 and 8. Using a flame tube combustor, the effect of fuel/air distribution and degree of vaporization can be studied. Also of great interest are soot formation and burnout, CO/NO_x formation trade-off, rich zone, quench zone and lean zone residence time effects, and quick quench mixing. Information obtained in the flame tube about these parameters will be used to guide the design of an RQL combustor.

The approach is to use a NASA-designed flame tube combustor to allow combustion testing at the high temperatures and pressures necessary for the HSR Program. This rig was specially designed for the HSR program using the latest combustion codes to predict the ideal fuel and air injection schemes as well as flame tube geometry and residence times in each stage of the combustor in order to minimize NO_x formation. It will also incorporate windowed sections to allow laser diagnostics to probe the premixing and combustion zones.

OBJECTIVE:

- ☐ **Demonstrate the Capability of RQL to Reach the HSR Goal of NO_x E.I.'s Between 3 and 8 g/Kg at Supersonic Cruise.**
- ☐ **Study:**
 - Fuel/Air Distribution and Atomization.**
 - Soot Formation and Burnout.**
 - CO/NO_x Formation Trade-off.**
 - Rich Zone, Quench Zone and Lean Zone Residence Time Effects.**
 - Quick Quench Mixing.**

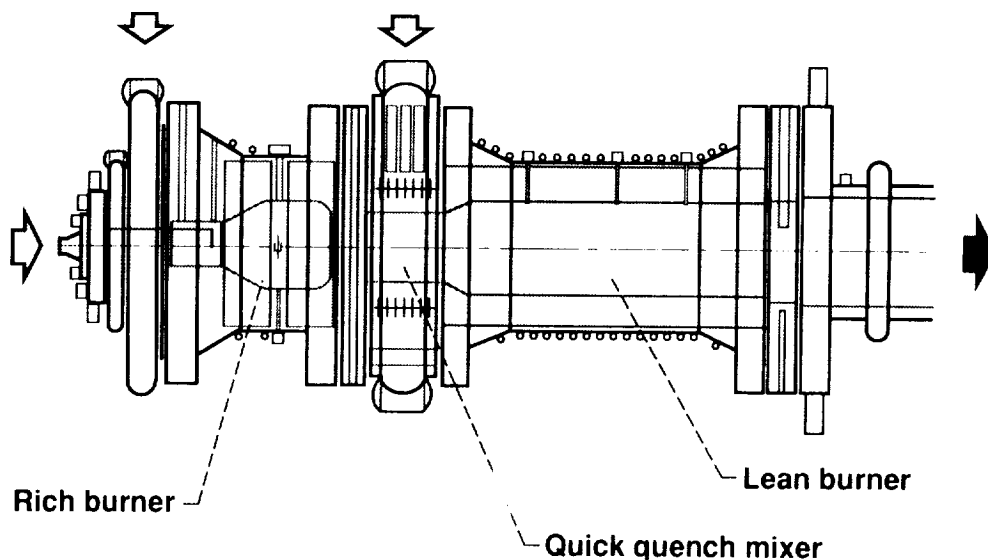
APPROACH:

- ☐ **Design and Build Staged Flame Tube Combustor to Reach the High Temperatures and Pressures Necessary for HSR Program.**
- ☐ **Use advanced laser diagnostics to obtain measurements and use in code validation.**

LeRC Rich Burn/Quick Quench/Lean Burn (RQL) Flame Tube Rig

The rig is shown schematically in this figure. The airflow, up to 5 lbs./second, 1100 F inlet temperature, 16 atmospheres pressure, passes through various passages entering the rich burn section. These passages supply air to various portions of the dome swirler fuel injection system (shown later). The fuel injection system can be modified by installing various fuel injectors having different airflow passages and swirler configurations. Future plans include the addition of a windowed section downstream of the fuel injector to allow flow visualization and laser diagnostic measurements of the degree of vaporization and droplet sizes and velocities in the rich burn section. The rich zone operates approximately at an equivalence ratio of 1.6. The combustion section is lined with a castable silicon-carbide ceramic and is externally water-cooled with copper cooling coils. The quick quench section supplies up to 11 lb./sec. airflow to produce a lean equivalence ratio of approximately 0.5 in the lean burn zone. Exhaust gas sampling is performed by an axially-traversing probe that takes samples in the lean burn section. A windowed section for the lean combustion zone is also planned for making laser induced fluorescence measurements of combustion species and temperatures.

Rich Burn/Quick Quench/Lean Burn Flame Tube Rig

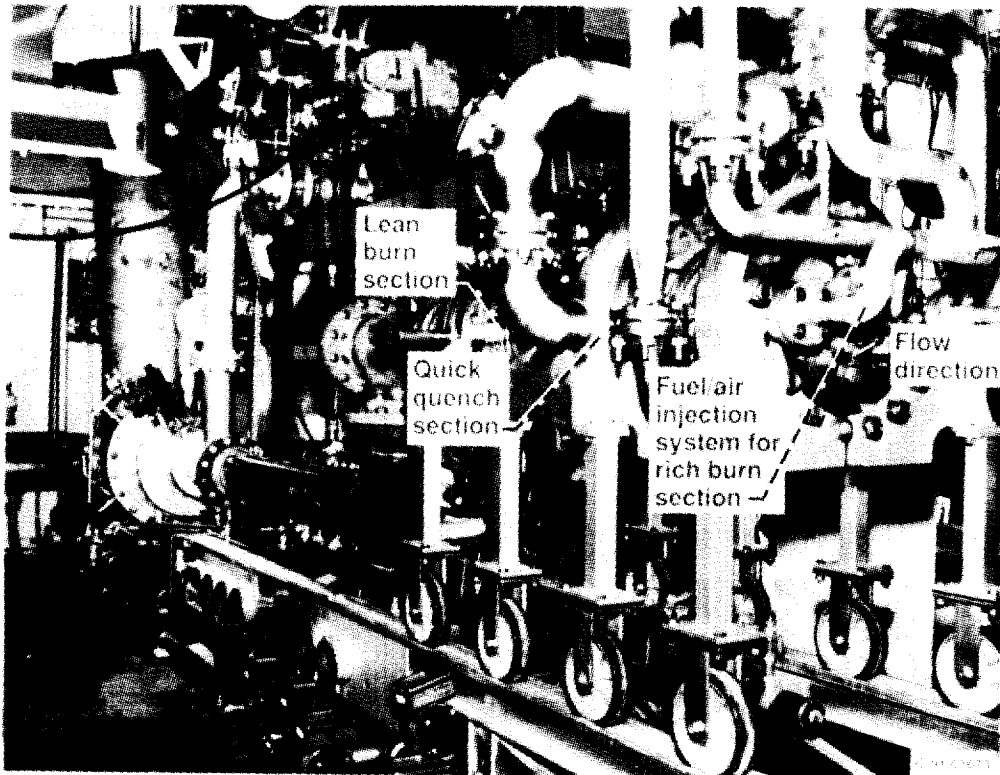


RQL Combustion

Photograph of RQL Rig

The RQL flame tube rig is shown in the photograph below. The non-vitiated pre-heated air passes into the rich burn section of the rig from the right-hand side of the picture through four air supply lines. These lines determine the air flow splits between the fuel injector inner and outer sections and the dome swirler. The large air inlet supply line for the quick quench section is shown, followed by the copper-coiled water-cooled lean burn section. The gas sampling probe will be mounted into the large flange at the end of the lean burn section. The wheels shown in the photo allow easy dismantling of the rig to allow installation of various length test sections to experimentally determine the optimum lengths for the rich and lean combustion zones.

LeRC In-House Rich Burn Quick Quench Lean Burn (RQL)
Flame Tube Rig



RQL Combustion

Airblast Fuel Injector System

The RQL flame tube rig airblast fuel injector system with the dome swirler is shown in the photograph below. Air passes through the system both inside and outside of the fuel-flow annulus. Air also passes through the dome swirler, shown as the outer passage with the large swirl vanes in this photograph. This fuel injector has exceeded the expectations of the manufacturer in its ability to produce extremely small fuel droplets. The effect of dome air versus inner and outer annulus air on fuel atomization and soot formation will be studied with this injection system.

**Airblast Fuel Injector System for LeRC RQL Flame Tube Rig
Showing Dome Swirler**

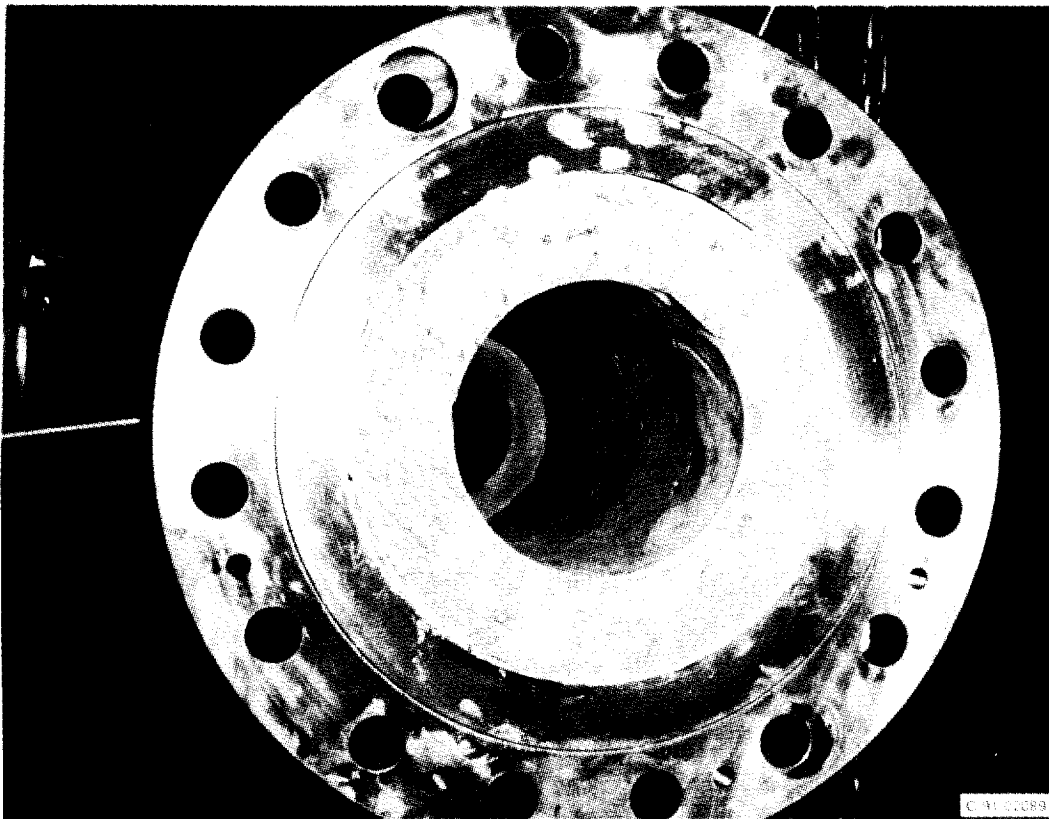


RQL Combustion

Rich Burn Section of RQL Flame Tube

The inside of the RQL flame tube rig rich burn section is shown in the photograph below. The entrance to the combustor as seen by the fuel injection system is shown as the foreground in this picture. The castable silicon carbide liner is shown and the transition from the 7-inch diameter combustion section to the 5-inch diameter quick quench section can be seen at the downstream end of this section. The liner is approximately 2-1/2 inches thick.

Rich Burn Section of LeRC RQL Flame Tube Rig



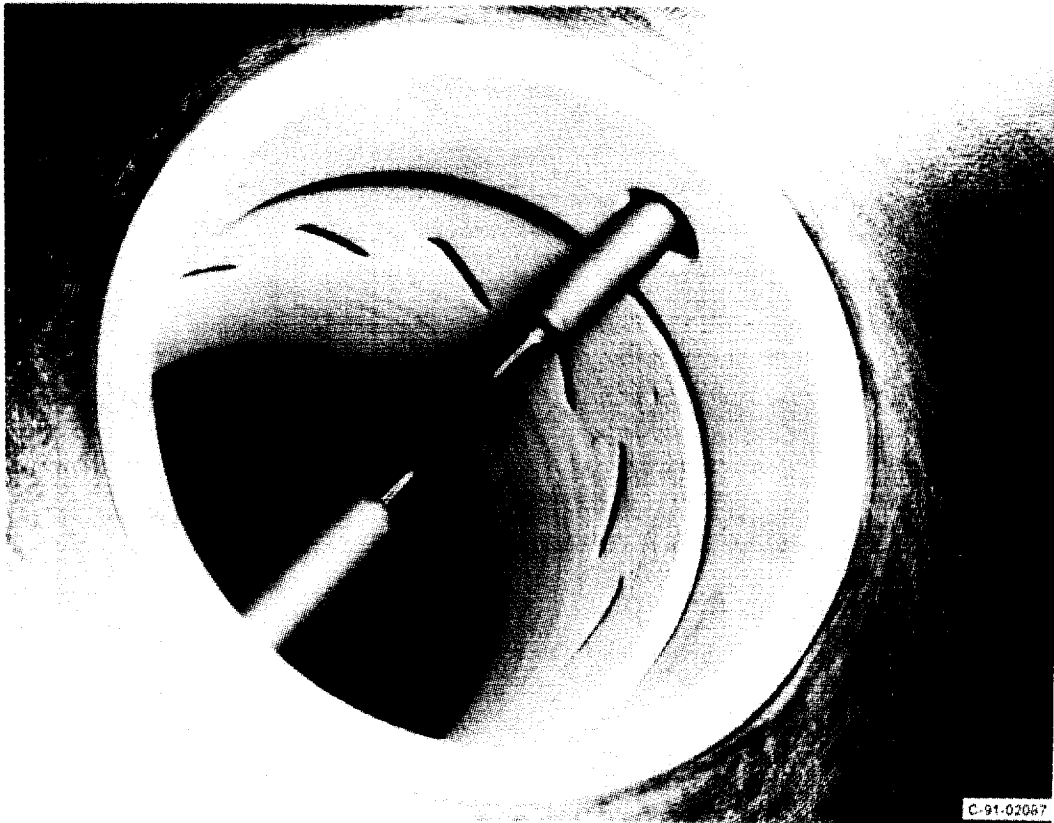
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RQL Combustion

Quick Quench Section of RQL Flame Tube

The RQL flame tube rig quick quench section is shown in the photograph below. Air passes into the quench zone through the 45-degree slanted slots seen behind the water-cooled thermocouple probes. These thermocouples determine the exit temperature of the rich burn section. The quench section shown is 5 inches in diameter. It is made of Haynes 214 material with a thin Rockide Z coating.

Quick Quench Section of LeRC RQL Flame Tube Rig



Fuel-Rich Catalytic Combustion

The objective of this part of the Lewis low NO_x program is to evolve the technology for utilizing liquid kerosene fuels in high speed combustion systems and to reduce NO_x and soot emissions through very rich catalytic oxidation and staged combustion. Some phenomena of interest include fuel vaporization and distribution, catalyst activity and physical characteristics, catalyst and substrate durability, and autoignition of the very reactive gases produced. Preliminary tests will be performed in a single stage catalytic combustor. A two-stage flame tube combustor will then be designed and tested in conjunction with the rich-burn/quick quench/lean burn flame tube combustor program so that this concept can be tested at the high temperatures and pressures necessary for the HSR program goals. All of the advanced diagnostics planned for use in the RQL rig will be available for use to evaluate the catalytic combustion section's contribution to the RQL concept.

OBJECTIVE:

- ☐ **Evolve the technology for utilizing liquid kerosene fuels in high speed combustion systems and reduce NO_x and soot emissions through very rich catalytic oxidation and staged combustion.**
- ☐ **Study:**
 - Fuel Vaporization and Distribution.**
 - Catalyst Activity and Physical Characteristics.**
 - Catalyst and Substrate Durability.**
 - Autoignition.**

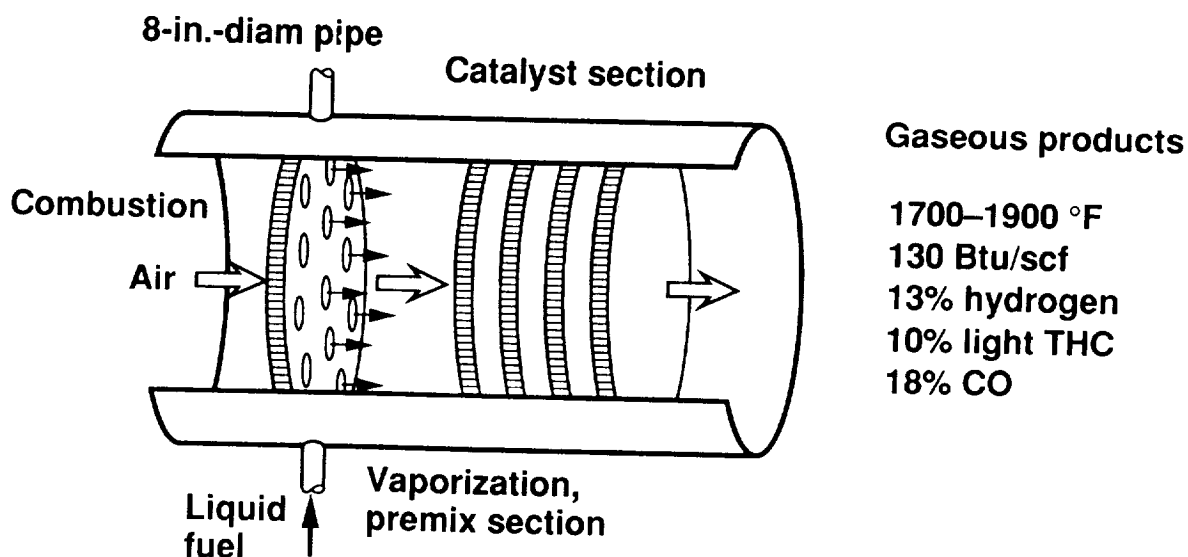
APPROACH:

- ☐ **Perform preliminary tests in a single-stage catalytic combustor**
- ☐ **Design and build a Two-Stage Flame Tube Combustor to reach the high temperatures and pressures necessary for HSR Program.**
- ☐ **Use advanced laser diagnostics to obtain measurements and use in code validation.**

Fuel-Rich Catalytic Combustion Test Rig

The main features of the single stage catalytic combustor are shown schematically below. In this concept, fuel greatly exceeds the available air by a factor of 3 to 9. Under these extremely fuel-rich conditions, catalytic elements are required to stabilize combustion downstream of the fuel injector and vaporization, premixing section. In the catalyst section, liquid JP fuel is transformed into a highly reactive, partially oxidized gas heated to 1700-1900 degrees F, well below the temperatures where NO_x and soot are formed. In a combustion system, this rich burn stage would be coupled with a quick quench stage and a final lean burn combustion stage. The combustion process produces large amounts of hydrogen, carbon monoxide, and partially oxidized hydrocarbons: all reactive species. Nitrogen oxide concentrations are 2.7 to 7.9 parts per million (where 100 parts per million would be required for an emission index of 1.0).

Fuel-Rich, Catalytic Oxidation Test Rig



Advanced Diagnostics

The objectives of the in-house programs in laser diagnostics is to provide non-intrusive means to measure flow characteristics in the LPP and RQL flame tube combustors. These measurements will provide data for code validation and for better understanding of both rich and lean combustion to develop design criteria for producing low NO_x combustors.

The flow characteristics of interest include the degree of fuel vaporization, flow and fuel droplet velocities, temperature profiles, chemical species and soot particle concentrations. Flow visualization techniques will also be performed which will provide information on fuel injector performance, mixing, and species concentrations.

OBJECTIVE:

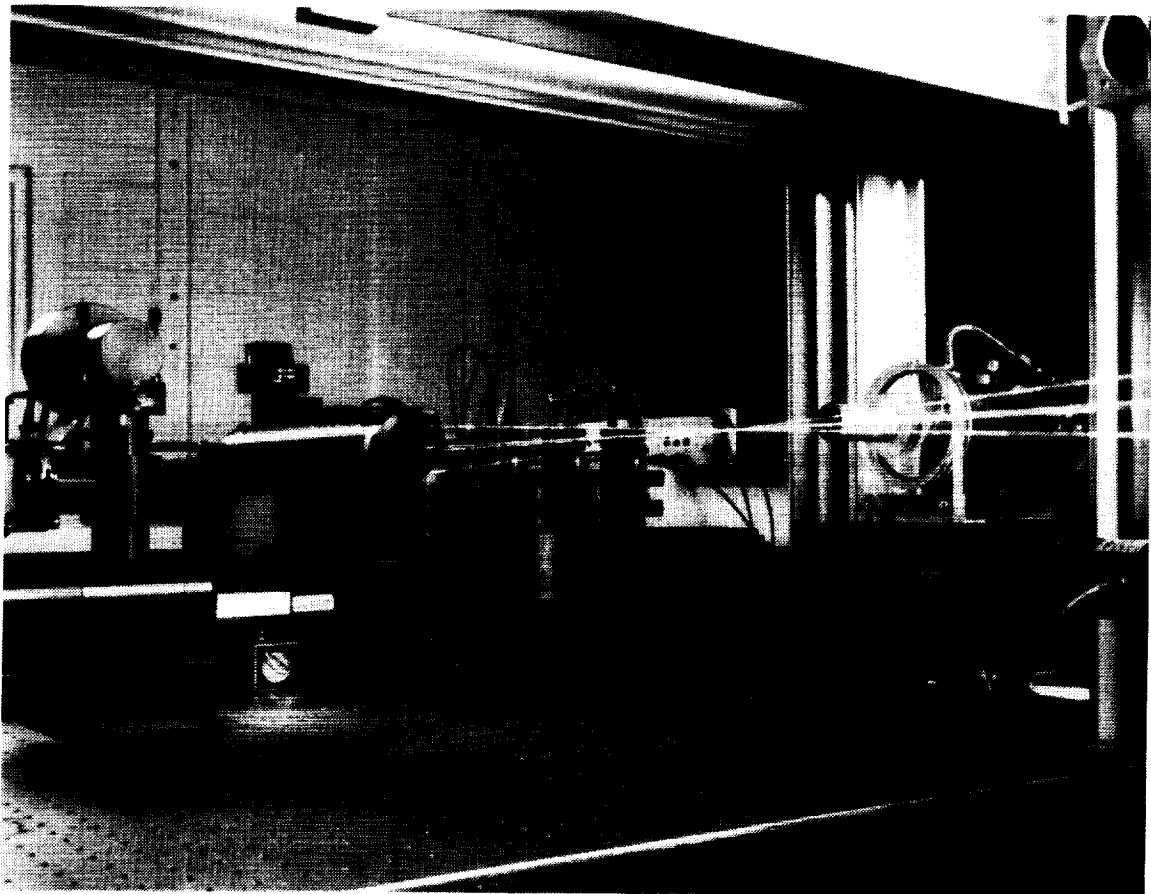
- ☐ **Provide advanced laser diagnostics to measure flow characteristics in flame tube combustors to better understand the physics and chemistry of combustion for the HSR Program.**
- ☐ **Study:**
 - Degree of Vaporization (Droplet Sizing)**
 - Flow and Droplet Velocities**
 - Temperature Profiles**
 - Species and Soot Particle Concentrations**
 - Flow Visualization (Fuel Injection, Mixing, Species)**

APPROACH:

- ☐ **Develop techniques both in-house and through university grants.**
- ☐ **Apply laser diagnostics to in-house flame tube rigs (LPP, RQL, Catalytic Oxidation).**

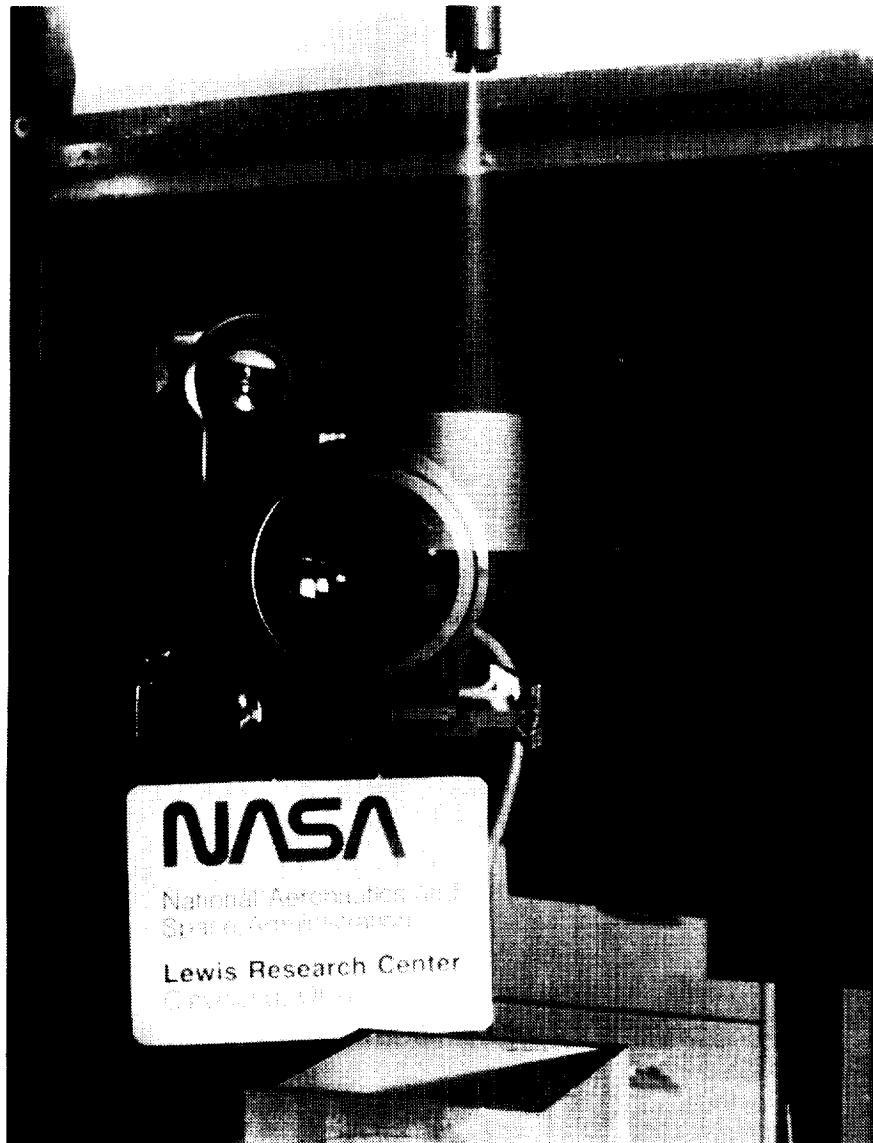
Flow Velocities

A three-component LDV system, using fiber optics, will provide flow velocity data to investigate recirculation zones within the premixing section and downstream of the flameholder, if possible. Flow velocity fields will provide information on the residence times involved in spray vaporization and flow residence times in the combustor, which will determine if local regions of high NO_x are being produced in recirculation zones in local high temperature regions. These measurements will be coupled with planned non-intrusive temperature measurements which will be provided by laser spectroscopy.



Fuel Spray Research

A copper vapor laser is used to illuminate and provide a strobe light source to allow flow visualization of fuel droplets in a test nozzle. In-house fundamental research on sprays, using advanced laser diagnostics will be applied to the LPP and RQL flame tubes after initial testing in simple, atmospheric bench tests such as the one seen in the photograph below. The copper vapor laser pulses at 10,000 hertz, allowing high-speed movies to be made of sprays, or allowing still photographs to be made of a spray by stopping the motion of the droplets. Phase Doppler Anemometry can be used to determine droplet velocities and sizes simultaneously in regions of interest after studying the flow visualization results. This information can be used to determine the fuel vaporization rates in a flame tube, validate codes, and be applied to future combustor designs.



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Measurement of Fuel Droplet Sizes

A Malvern particle sizer will be used to obtain fuel spray droplet sizes. This laser technique provides a line-of-sight measurement and supplies a mean droplet size to characterize the spray. This instrument will be used to study the vaporization process in the flame tube combustors (LPP and RQL) where access to the premixing sections is provided by quartz windows.

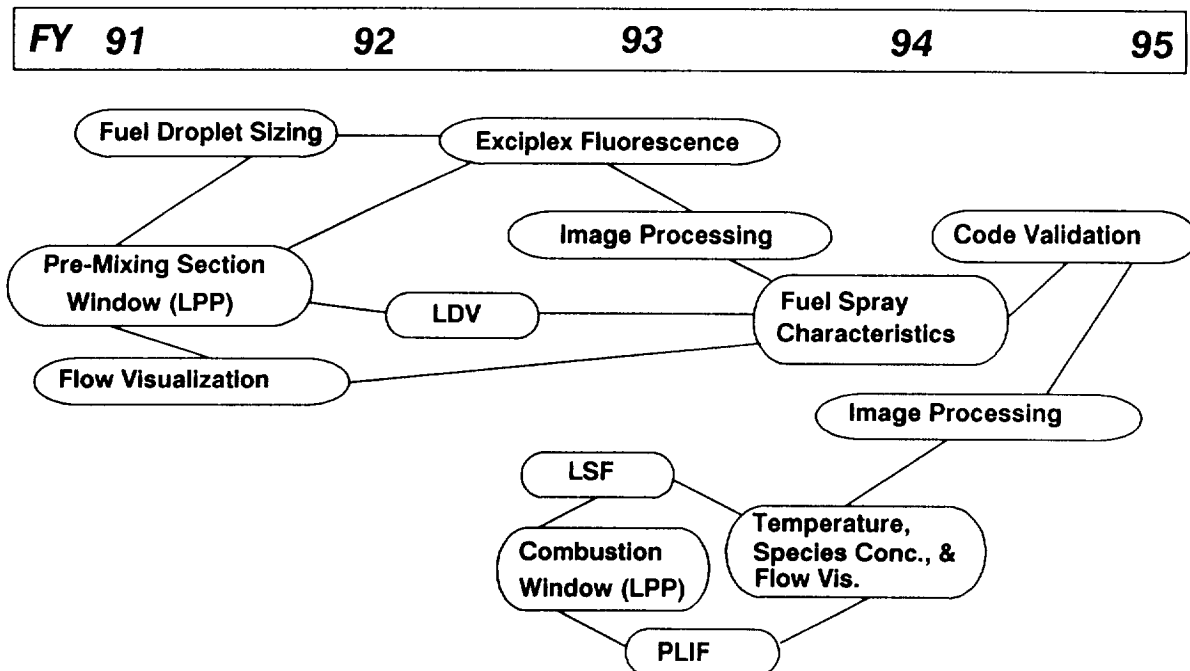


Advanced Diagnostics Schedule

The general schedule for employing various diagnostic techniques is schematically shown below. Initially, the pre-mixing section of the LPP rig will be probed with flow visualization techniques including still photography, laser-strobe photography, and schlieren photography. The Malvern particle sizer will then be used to provide fuel droplet sizes. Laser Doppler Velocimetry will be used to determine flow velocities. Later work will include application of exciplex fluorescence to determine the degree of vaporization at different positions in the premixing section. Digital image processing will be performed on the 2D images of the vapor vs. liquid concentrations to determine the extent of vaporization.

The combustion zone will be probed using laser saturated fluorescence and planar laser induced fluorescence to determine species concentrations (OH and NO) and temperature profiles. The planar measurements will be image processed to provide quantitative results. Soot measurements will be made in the RQL rig using laser scattering/extinction point measurements.

The diagnostics results from the premixing and the combustion sections from both the LPP and RQL rigs will be used to validate codes that will be used to develop low NO_x combustor designs.



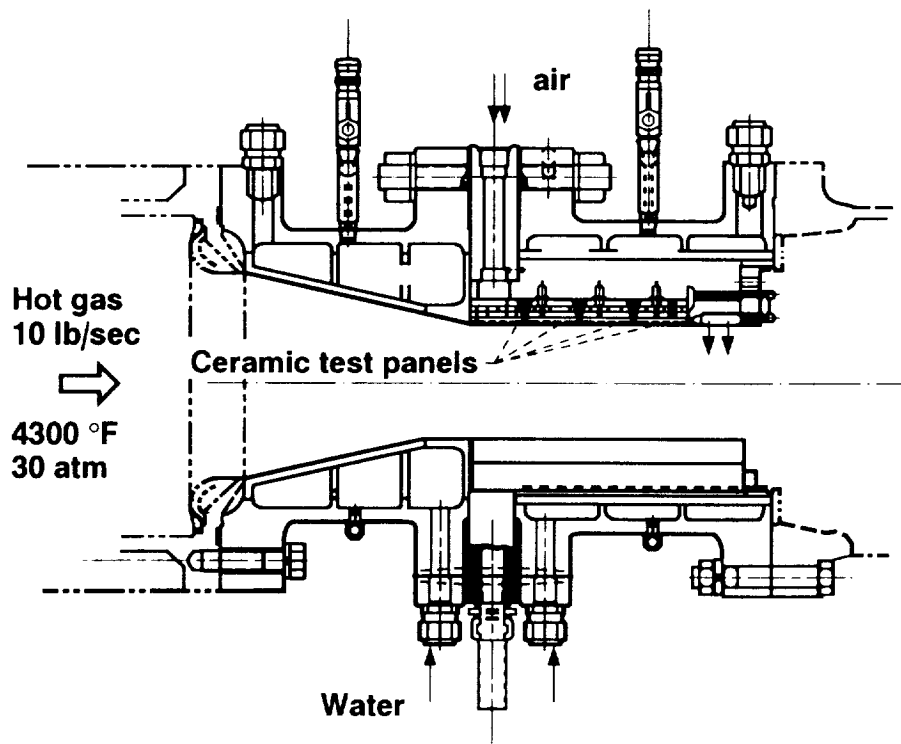
Ceramic Matrix Liner Test Rig

The ceramic matrix liner test rig was specially designed to evaluate advanced ceramic/composite materials under the extreme operating conditions which will be required by future advanced gas turbine engines. A slave combustor provides very hot (up to 4300 degrees F) high pressure (to 30 atm.), inlet gases at flow rates up to 10 lb./sec. Up to 16 separate ceramic test panels can be arranged inside the square test section such that each set of four can have different back-side cooling conditions. The rig itself is water-cooled to withstand the extreme operating conditions. This rig is nearing final installation stages and will soon be available to the materials and gas turbine engine community for use in the Enabling Propulsion Materials Program part of the HSR Program.

Ceramic Matrix Liner Test Rig

Objective:

Evaluate advanced ceramic/composite materials under advanced engine conditions.



Summary

The NASA Lewis In-House research program has produced encouraging results from the Lean Premixed Prevaporized flame tube rig, producing NO_x emission indices less than 3 gms./kg. fuel at an inlet temperatures of 930 F and pressure of 10 atm. Future plans call for increasing the inlet pressures and temperatures to encompass the whole HSR cruise condition range.

The RQL rig is well underway and will soon produce the first gas sampling probe data on NO_x levels from a flame tube designed with the latest analytical tools to produce low NO_x. Both the rich and the lean zones will have gas sampling probes installed. This rig will also provide operating conditions that will simulate the whole HSR cruise range. The operating parameters for the rich, quench and lean zones will be defined, for use in engine combustor design.

Advanced laser diagnostics are planned for fuel injection and combustion studies which will supply non-intrusive measurements of fuel vaporization, mixing, and chemical species concentrations.

The catalytic combustion program will continue to provide fundamental data that will be used to build a complete catalytic test section that will serve as the rich burn stage of the RQL combustor for two-stage experiments which will begin in FY92.

- **The LeRC LPP Rig has provided ultra-low NO_x data: E.I.'s of 1-3 gms./kg. at HSR cruise conditions.**
- **The LeRC RQL rig is in the initial check-out stages and will provide experimental NO_x data by summer, 1991.**
- **Advanced laser diagnostic systems are being set up for fuel injection and combustion studies in flame tubes.**
- **Two-stage experiments in catalytic combustion will begin in FY 92.**

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